OPTION 2A
HYDROGEN

Hydrogen is not a fuel but an energy carrier used to transfer energy from one place to another. This distinction allows a variety of feedstocks for applications in which their use would be otherwise difficult, such as coal or water for light-duty vehicles.

Hydrogen has to have an energy source such as solar, wind, nuclear, or conventional power, to produce it and a feedstock to provide the hydrogen. The pathways for hydrogen production can be divided into three major categories by energy source: fossil-based hydrogen, renewable-based hydrogen, and nuclear-based hydrogen. The many potential combinations, illustrated in Table 1, make it difficult to determine the pathways that will be the choices for the future.

Table 1. Hydrogen Production Options

Raw Feedstocks	Processed Feedstocks	Process Options	Process Energy Source Options
• Fossil Fuels Natural Gas Coal Oil • Renewables Crops Biomass • Water	• Direct Use • Syngas • Gasoline • Diesel • Methanol • Ethanol • Ammonia • Biodiesel • Biogas • Sugars	• Steam Reforming • Partial Oxidation • Gasification • Pyrolysis • Electrolysis • Photoelectro-chemical • Aerobic Fermentation • Anaerobic Fermentation	Thermal/Electricity Source • Fossil Fuels • Renewables • Nuclear

The potential for hydrogen to be developed from such a wide variety of feedstocks is promoting worldwide interest. Countries can develop hydrogen from sources which they have abundance, using thermal and electricity options that are the least expensive for them. Collaborations of government agencies and private industries have formed, from statewide (California Fuel Cell Partnership or CaFCP) to worldwide (International Partnership for the Hydrogen Economy) to increase the use of hydrogen as an energy carrier.

The National Academy of Sciences National Research Council's Committee on Alternatives and Strategies for Future Hydrogen Production and Use believes for hydrogen transportation, the four most fundamental challenges to be overcome are:

- Durable, safe, and environmentally desirable fuel cell systems and hydrogen storage systems have to be developed.

- Hydrogen infrastructure has to be provided for the light-duty vehicle user.

- The cost of hydrogen production from renewable resources has to be sharply reduced.

- CO_2 by-products of hydrogen production from coal have to be captured and sequestered.[1]

Currently, hydrogen is commonly produced from natural gas using steam methane reforming. This feedstock is not produced from domestic sources in amounts that could support the amount of hydrogen needed for transportation use. Thus, any reductions in petroleum imports would be offset by an increase in natural gas imports.

The cost of hydrogen produced from natural gas will depend on the plant size, the efficiency of the system, and the cost of natural gas. The National Academy of Sciences has estimated the effects of the price of natural gas on the cost of hydrogen at plants of three different sizes as illustrated in Table 2. The costs of hydrogen are based on current steam methane reforming technology.

Table 2. Conversion of Natural Gas to Hydrogen

Size of Plant	Natural Gas Price ($/mmBtu)						
	$2.50	$3.50	$4.50	$5.50	$6.50	$7.50	$8.50
	$ per kg hydrogen (no CO_2 sequestration)						
1.2 million kg hydrogen per stream day	$0.68	$0.86	$1.03	$1.21	$1.38		
0.024 million kg hydrogen per stream day	$1.03	$1.21	$1.38	$1.56	$1.73		
480 kg hydrogen per stream day			$3.04	$3.28	$3.51	$3.75	$3.98

*CO_2 sequestration may raise the cost of hydrogen by approximately 11 percent to 20 percent depending on plant size and natural gas price.

Research continues on feedstocks or energy sources for hydrogen production to be used as a source of hydrogen. To gain perspective on the relative scale of producing hydrogen from various sources, Tables 3a and 3b were derived from the U.S. Department of Energy (DOE) summary of hydrogen production from domestic resources. About 242 kg of hydrogen per vehicle per year[2] or 0.27 short tons of hydrogen per vehicle per year[3] is a basic assumption in the DOE analysis. The values in column (a) represent 100 percent going to the production of the hydrogen. Thus, over six times as much biomass and three times as much coal will be needed to produce the same amount of hydrogen as natural gas, given current technologies. Similarly, over twice as much as nuclear energy will be required to produce hydrogen from water with wind or solar energy.

Table 3a. Potential Hydrogen Production from Reforming or Partial Oxidation Processes

Feedstock	(a) Amount Required Per Vehicle Per Year if providing 100% of feedstock requirement (tons)	(b) Total amount required for 30,000 Vehicles (tons)	(c) 2003 Amounts Used or Produced in California (tons)
Natural Gas	0.63	19,000	7,565,503 [a]
Biomass	4.00	120,000	10,970,345 [b]
Coal	2.07	62,000	0

[a]Includes amounts used for electricity production.

[b]Biomass residue calculated from California agricultural statistics on acreage (California Agricultural Statistics Services and County Agricultural Commissioners annual reports) and UC Davis data on residue tons per acre.

Table 3b. Potential Hydrogen Production From Water Electrolysis

Source of Electricity	(a) Amount Required Per Vehicle Per Year if providing 100% of electricity requirement (megawatts)	(b) Total electricity required for 30,000 Vehicles (megawatts)	(c) 2003 California Gross System Power[4] (megawatts)
Wind	0.0037	111	486
Solar	0.0049	148	85
Nuclear	0.0014	43.2	4052

Technology options for using hydrogen as a transportation fuel are also varied. Hydrogen gas can be burned in an internal combustion engine (ICE) and gasoline can provide the hydrogen for a fuel cell. Determining market penetration dates is fraught with uncertainty. As seen in Table 4, DOE has targeted 2015 to make the decision whether to continue commercialization based on the ability of hydrogen technology to meet customer requirements at that time. The timelines shown do not include research and development being conducted in other countries through the

International Partnership for the Hydrogen Economy. Technology breakthroughs outside California or the U.S. would impact domestic critical path decisions.

Table 4. Timelines for Transition to Hydrogen

Year	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
CaFCP[5]	65 fuel cell vehicles			300 fuel cell vehicles and stations to support them (includes 7 buses)																	
DOE Hydrogen Program Plan	Research and development programs										Go/No-go commercialization decision										
						Transition of programs to marketplace															
	Govt. fleets					Other vehicle fleets										Vehicle market intro.					
	Hydrogen from advanced processing of natural gas																				
						Hydrogen from gasification of coal (85%)/biomass (15%) with sequestration credits from growing cycle of biomass															
						Hydrogen from electrolysis of water using nuclear and renewable fuels															
ISHRI[6]						Production of low-cost hydrogen from domestic coal with the capture and sequestration of CO_2															

Hydrogen Development Worldwide

A partial list of worldwide hydrogen projects illustrates the commitment of financial and scientific support to develop and commercialize the necessary technologies.

- The Japanese government has committed to install over one million fuel cells in family houses and to have 50,000 fuel cell vehicles on the road by 2010.

- Mazda Motor Corporation plans road tests between 2005 and 2007 for a dual-fuel hydrogen rotary engine featuring an electronically controlled hydrogen gas direct injection system. Rotary engines, less fuel efficient than reciprocating engines on gasoline, are more efficient than standard engines on hydrogen. Mazda also installed a hydrogen filling station in Hiroshima, Japan.

- In Iceland, hydrogen buses are being tested.

- Australia is converting thousands of postal bikes to fuel cells.

- After a five-year evaluation period, the Italian government approved service use of a 60kW fuel cell and battery hybrid bus for the city of Turin.

- The world's largest hydrogen filling station, capable of filling more than 100 vehicles per day, has opened in Berlin, Germany. Aral (a subsidiary of Deutsche BP) is offering hydrogen alongside gasoline and diesel at a conventional filling station.

- The Michelin Group of France and the Paul Scherrer Institute of Switzerland have developed a prototype lightweight fuel cell vehicle. The weight of the car's materials allows its fuel consumption to be spectacularly low.

- The U.S. Army has been working on a high-performance, off-road fuel cell vehicle for high mobility in stealth operations. The vehicle runs on compressed hydrogen and can reach 40 miles per hour, twice as fast as conventional gasoline ICE all-terrain vehicles.

Hydrogen for Transportation

In transportation, hydrogen can be used with fuel cell vehicles and ICE with modifications, including vehicles that run on natural gas or propane. Hydrogen and natural gas blends may provide a transition to hydrogen-powered vehicles.

Fuel Cell Vehicles

Several types of fuel cells are being developed, but the one being considered in transportation applications is the Proton Exchange Membrane (PEM) fuel cell. The PEM fuel cell has a high power density, operates at low temperatures, permits adjustable power output, and allows quick start-ups.[7]

PEM fuel cell vehicles use hydrogen gas stored on the vehicle in gaseous or liquefied form in tanks, or liquid fuels converted to hydrogen using an on-board reformer.

Since 2000, 65 light-duty fuel cell vehicles have been traveling California roads for demonstration and testing through the CaFCP. The companies and models are:

- DaimlerChrysler – F-Cell, based on the European Mercedes-Benz A-Class
- Ford – Focus FCV
- General Motors – Hy-wire and HydroGen3
- Honda – FCX
- Hyundai Motor Company – Santa Fe FCEV
- Nissan
- Toyota – FCHV-4
- Volkswgen – Touran HyMotion

Table 5 provides information on two fuel cell vehicles reported in the U.S. Environmental Protection Agency's (EPA) Fuel Economy Guide.

Table 5. 2005 Fuel Cell Vehicles Listed in EPA Fuel Economy Guide[8]

	Honda FCX	Ford Focus FCV
Miles/kg hydrogen	51 to 62	48 to 53
Range	190 miles	200 miles
Vehicle Class	Subcompact	Compact
Type of Fuel Cell	PEM	PEM
Motor	80 kW DC brushless	65 kW AC induction
Energy Storage	9.2 farad ultracapacitor	180 V NiMH battery

Fuel cell vehicles can use direct hydrogen or an on-board reformer using ethanol, methanol, or gasoline. The preponderance of data is associated with direct hydrogen (compressed or liquefied) use. This analysis will focus on this technology. However, it is possible fuel cell vehicles will be introduced using gasoline reformers to gain the benefits of increased fuel economy and decreased emissions while using existing gasoline fueling infrastructure.

An additional public benefit of the fuel cell vehicle technology is the concept of the “skateboard” chassis with “snap-on” bodies. The possibility of extremely compact all-electronic designs through the elimination of mechanical parts could decrease the cost of vehicle production. The benefits associated with this aspect of fuel cell technology will be developed during the transition phase to the marketplace, currently projected to be between 2010 and 2020.

Hydrogen in Internal Combustion Engines

Getting an internal combustion engine to run on hydrogen is not difficult. The challenge is getting an internal combustion engine to run well on hydrogen.

If hydrogen is mixed with natural gas, both can be stored in the same tank. Liquid hydrogen must be stored in a separate vessel because of its extremely low temperature. If used with liquid fuels such as gasoline or diesel, hydrogen has to be stored separately and mixed prior to ignition. [9]

To test the potential for reduced emissions and increased fuel economy with hydrogen-compressed natural gas (CNG) blends, the Arizona Public Service Company (APS), Electric Transportation Applications, and the DOE’s Advanced Vehicle Testing Activity tested four vehicles:

1. A Dodge Ram Wagon van, a factory produced dedicated CNG vehicle[10];

2. A 2000 model year Ford F-150, factory equipped with a CNG engine that was modified to run on a 30 percent hydrogen with CNG blend[11];

3. A 2001 model year Ford F-150, factory equipped with a gasoline engine that was modified to run on a 30 percent hydrogen with CNG blend initially and later, on a 50 percent hydrogen with CNG blend[12]; and

4. A 1998 model year Mercedes Sprinter van, factory equipped with a 2.4 liter gasoline engine that was converted in Germany to operate on pure hydrogen[13].

Emissions comparisons on the Fords were made against a similar gasoline vehicle, using California emission requirements as a reference. The 50 percent hydrogen blend vehicle was tested at the Clean Air Vehicle Technology Center in California. Further work needs to be conducted, but overall, emission reductions were achieved, particularly in the 50 percent hydrogen blend. Total hydrocarbon emissions showed a 7.5 percent drop and carbon dioxide was reduced by almost 30 percent. Where tracked, fuel economy gains were made proportional to the amount of hydrogen in the blend. The Mercedes Sprinter van was only operated for about 4,000 miles; therefore the fuel economy may be erroneously high. The tests concluded a re-tuned, factory dedicated CNG vehicle can provide operating results comparable to a gasoline vehicle converted for hydrogen blends. Also, the CNG vehicle required less work to run well on hydrogen than the ICE vehicle.

Ford Motor Company has developed an ICE optimized to burn hydrogen instead of gasoline. The engine can reach an overall efficiency of about 38 percent, about 25 percent more fuel-efficient than a typical gasoline engine, and its emissions are nearly zero. The engine is based on Ford's 2.3 liter engine used in the Ford Ranger. Supercharging allows the hydrogen ICE to deliver the same power as its gasoline counterpart.[14]

The Difficulty in Estimating Future Hydrogen Penetrations

Future hydrogen vehicles include various combinations such as:

- Internal combustion engines using hydrogen gas,
- Internal combustion engines using a hydrogen and natural gas mix,
- Proton exchange membrane (PEM) fuel-cell stack using an on-board reformer and a liquid fuel such as methanol, ethanol, or gasoline, and
- PEM fuel-cell stack using direct hydrogen generated off-board and stored on the vehicle in compressed or liquid form.

The hydrogen vehicles of the future may also be any or all of the above combinations. The cost increment depends on the variations. A direct hydrogen fuel cell vehicle with a 60-kW PEM and a 25-kW battery will cost more than a direct hydrogen fuel cell vehicle with a 25-kW PEM and a 60-kW battery.[15]

In modeling the cost effectiveness of various zero-emission vehicle technologies such as hybrid electric, electric, and hydrogen fuel cell vehicles; RAND Corporation estimated production volumes that could impact cost would not be achieved until 2020.[16]

In October 1999, DOE, the California Air Resources Board (CARB), and the California Energy Commission (Energy Commission) co-sponsored a workshop to answer the question: *What has to be done, beginning today, to implement a hydrogen fuel infrastructure so that when hydrogen vehicles become market-ready in 3-5 years, the infrastructure needed for on-board direct use of hydrogen will be available?* In summary, the workshop and subsequent planning meetings identified (1) the rate of hydrogen technology development and (2) the interplay between market forces and social concerns as the key drivers that would determine the role of hydrogen in plausible energy futures.

Key uncertainties identified were:

- the nature of hydrogen technology development,
- the rate of hydrogen technology development, and
- how social concerns such as environmental quality and energy security affect competitive market forces that determine fuel choice and the commercial success of advanced technologies.[17]

Six years later, hydrogen fuel cell vehicles are being tested and demonstrated in limited numbers. An equally limited number of ICE vehicles are being run on hydrogen. To advance the number of vehicles penetrating the market significantly prior to 2020 will require fundamental breakthroughs in both fuel cells and hydrogen production.

Assumptions for Vehicle Penetration Scenarios

Due to the uncertainties of hydrogen technology development, values for fuel displacement, consumer savings, and changes in government revenue are preliminary numbers that will be revised in future reports. It is assumed three types of hydrogen vehicles will be introduced in California, first for fleet use and then to the public market.

1. Natural gas vehicles optimized to use between 30 percent to 50 percent hydrogen (by volume) – average 30 miles per gasoline gallon equivalent.

2. ICE designed for 100 percent hydrogen – 30 miles per gasoline gallon equivalent.

3. PEM fuel cell vehicles using direct hydrogen, with full market penetration occurring in 2020 – 74 miles per gasoline gallon equivalent.

The gasoline gallon equivalent (gge) was determined for the various fuel mixtures using the following values defined by the National Conference of Weights and Measures.[18]

- CNG: 2.57 kg/gge
- 30% hydrogen blend by volume: 2.41 kg/gge
- 50% hydrogen blend by volume: 2.22 kg/gge
- Hydrogen: 1.04 kg/gge

Shell Hydrogen is collaborating with General Motors to demonstrate refueling infrastructure technology. The company's goal is to provide hydrogen alongside traditional fuels. Their plan is for networks of stations between 2010 to 2020. ChevronTexaco and BP have also announced similar involvement to provide hydrogen infrastructure.

ICE Using Direct Hydrogen

Fuel economy for hydrogen and hydrogen-natural gas blend vehicles were estimated using a combination of the gasoline gallon equivalencies, EPA fuel economy ratings for compressed natural gas vehicles, data from Ford regarding their hydrogen optimized ICE, and operational data from APS operating summaries.

Fuel cost ranges for the hydrogen blends were based on the relative percentages of hydrogen and natural gas. Table 6 summarizes the average petroleum reduction and direct non-governmental benefits for the hydrogen ICE vehicle option.

Table 6. Average Petroleum Reduction and Direct Non-Governmental Benefits for Hydrogen ICE

	Average Conventional Fuel Displaced (billions gallons)	Average Consumer Savings 12% to 5% discount rate	Average Change in Gov't Revenue 12% to 5% discount rate
2005 to 2010	0.009	($8) to ($9)	($4) to ($5)
2005 to 2020	0.761	($375) to ($742)	($166) to ($446)
2005 to 2025	1.544	($841) to ($2,075)	($357) to ($1,191)

Fuel Cell Vehicle Using Direct Hydrogen

With current technologies, direct hydrogen use in a fuel cell provides the highest efficiency. The hydrogen storage options for the lowest cost during the period of 2005 to 2015 will probably be compressed or liquefied hydrogen.

Argonne National Laboratories Fuel Cell Program established energy storage requirements for three vehicle platforms (compact car, mid-size car, and sport utility vehicle) using 2005 to 2007 fuel cell technologies. Argonne's Center for Transportation Research (CTR) developed baseline models, assuming compressed hydrogen and PEM fuel cell systems. The models showed the fuel economy of the mid-term hydrogen fuel cell vehicles to be 2.5 to 2.7 times the fuel economy of the current conventional gasoline ICE on the same vehicular platform.

Argonne used a 320-mile driving range between refueling. This data was used to estimate the relationship between fuel economies of hydrogen fuel cell vehicles and their ICE counterpart. Table 7 summarizes relative fuel economy data for fuel cell and ICE vehicles.

Table 7. Relative Fuel Economy of Fuel Cell Vehicle to ICE Vehicle

	Compact Car	Mid-Size Car	SUV
Modeling Range	320 miles	320 miles	320 miles
Compressed Hydrogen Used	4.3 kg	5.1 kg	6.4 kg
Fuel Cell Vehicle Economy	74 miles/kg	62 miles/kg	50 miles/kg
Conventional ICE Fuel Economy	28 miles/gallon	23 miles/gallon	20 miles/gallon
Ratio[19]	2.64 gallons gas/kg hydrogen	2.7 gallons gas/kg hydrogen	2.5 gallons gas/kg hydrogen

Incremental cost estimates of $9,000 to $11,000 made by Arthur D. Little for the 2010 to 2020 time period were used. The number of vehicles was assumed to be 10 percent of the estimated U.S. population of 3 million vehicles by 2020. Both vehicle and hydrogen production technologies are assumed to be in transition to full commercialization during the period of this analysis. Table 8 summarizes average petroleum reduction and direct non-environmental benefits for a hydrogen fuel cell vehicle.

Table 8. Average Petroleum Reduction and Direct Non-Environmental Benefits for Hydrogen Fuel Cells

	Average Conventional Fuel Displaced (billions gallons)	Average Consumer Savings 12% to 5% discount rate	Average Change in Gov't Revenue 12% to 5% discount rate
2005 to 2010	0.000	($1) to ($1)	($0) to ($0)
2005 to 2020	0.310	($148) to ($429)	($40) to ($101)
2005 to 2025	0.759	($456) to ($1,735)	($149) to ($436)

Endnotes

[1] National Academy of Sciences,The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs, 2004.

[2] Number derived from DOE Hydrogen Posture Plan and verified with current fuel cell vehicle ranges of 48 to 51 miles per kilogram (approximately 12,000 to 15,000 miles per year travel).

[3] Approximately 907.185 kg per short ton hydrogen.

[4] http://www.energy.ca.gov/electricity/gross_system_power.html (April, 27, 2005)

[5] California Fuel Cell Partnership 2005 Program Plan, January 25, 2005.

[6] Integrated Sequestration and Hydrogen Research Initiative.

[7] Arthur D. Little, Projected Automotive Fuel Cell Use in California, October 2001.

[8] U.S. Department of Energy, Fuel Economy Guide for 2005 model year vehicles.

[9] Hydrogen Use in Internal Combustion Engines, College of the Desert, December 2001.

[10] Karner, Don and James Francfort, *Dodge Ram Wagon Van – Hydrogen/CNG Operations Summary*, Idaho National Engineering and Environmental Laboratory, INEEL/EXT-03-00006 (January 2003).

[11] Karner, Don and James Francfort, *Low-Percentage Hydrogen/CNG Blend Ford F-150 Operating Summary*, Idaho National Engineering and Environmental Laboratory, INEEL/EXT-03-00008 (January 2003).

[12] Karner, Don and James Francfort, *High-Percentage Hydrogen/CNG Blend Ford F-150 Operating Summary*, Idaho National Engineering and Environmental Laboratory, INEEL/EXT-03-00007 (January 2003).

[13] Karner, Don and James Francfort, *Hydrogen-Fueled Mercedes Sprinter Van Operating Summary*, Idaho National Engineering and Environmental Laboratory, INEEL/EXT-03-00009 (January 2003).

[14] Ford Motor Company – Hydrogen Internal Combustion, www.ford.com/en/innovation/engineFuelTechnology/hydrogenInternalCombustion.htm

[15] Rand, *Driving Emissions to Zero: Are the Benefits of California's Zero Emission Vehicle Program Worth the Costs?*, MR1578 (2002).

[16] Ibid.

[17] National Renewable Energy Laboratory, *Integrated Hydrogen Fuel Infrastructure Research and Technology Development*, NREL/CP-570-28890 (2000).

[18] Idaho National Engineering and Environmental Laboratory, U.S. Department of Energy FreedomCAR & Vehicle Technologies, Advanced Vehicle Testing Activity operating summaries, January 2003.

[19] The fuel economy ratios were checked against data provided by Arthur D. Little in their report, Projected Automotive Fuel Cell Use in California – (data from 2000 technology) for a hypothetical 600 mile range:

Compressed Hydrogen Fuel Cell Vehicle	0.90 miles/MJ hydrogen
Conventional ICE Vehicle	0.43 miles/MJ gasoline
Ratio	2.1 gasoline/hydrogen